Z

BRL

REPORT NO. 1165
MARCH 1962

AN APPLICATION OF THE JET-FORMATION THEORY TO A 105MM SHAPED CHARGE

F. E. Allison
R. Vitali

Department of the Army Project No. 503-04-002
Ordnance Management Structure Code No. 5010.11.815
BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

ASTIA AVAILABILITY NOTICE

Qualified requestors may obtain copies of this report from ASTIA.

The findings in this report are not to be construed as an official Department of the Army position.

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

REPORT NO. 1165

MARCH 1962

AN APPLICATION OF THE JET-FORMATION THEORY TO A 105MM SHAPED CHARGE

F. E. Allison

R. Vitali

Terminal Ballistics Laboratory

Department of the Army Project No. 503-04-002
Ordnance Management Structure Code No. 5010.11.815

A B E R D E E N   P R O V I N G   G R O U N D ,   M A R Y L A N D

Page intentionally blank

Page intentionally blank

Page intentionally blank

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

REPORT NO. 1165

FEAllison/RVitali/iv
Aberdeen Proving Ground, Md.
March 1962

AN APPLICATION OF THE JET-FORMATION THEORY TO A 105MM SHAPED CHARGE

ABSTRACT

The equations describing the cone-collapse and jet-formation process are shown to be in excellent agreement with the emerging-jet-velocity, radioactive-tracer, and slug-recovery data for the 105mm unconfined test charge. Because the number of parameters measured experimentally exceeds the number needed to solve the equations, compatibility of the data with the equations shows that the non-steady theory correctly describes the formation of that portion of the jet able to penetrate mild steel.
A polynomial representation of the collapse velocity is obtained which is believed sufficiently accurate for most problems requiring values for this parameter.

INTRODUCTION

This report presents numerical results from an accurate computation of the liner collapse velocity for a 105mm shaped charge. A drawing of the charge, together with a table of pertinent dimensions, is presented in Figure 1. In addition to obtaining values for the collapse velocity, it is also shown that the available data for this charge are compatible with the currently accepted theory of liner collapse and jet formation.

The first published theory describing the formation of a high-speed metallic jet by a lined-cavity charge appeared in the Journal of Applied Physics for June, 1948[1]. The mathematical description of the process was based on steady-state hydrodynamics and predicted the formation of a jet whose length was constant and equal to the slant height of the cone. There was, however, ample experimental evidence to show that jets formed by shaped charges contained a spectrum of velocities with the front of the jet traveling much faster than the rear. In order to describe the velocity gradient in the jet, Pugh[2] and his associates developed a more general theory of the jet-formation process. The generalized theory is based on the same steady-state hydrodynamic concepts as the original theory; however, the collapse velocities of the liner elements are no longer assumed to be the same for every element, but are allowed to vary according to the position of the liner element within the charge. The pertinent equations describing the collapse of a conical shaped-charge liner by a plane detonation wave propagating parallel to the axis of the charge are:[2]

$$\delta = \sin^{-1}(V_o/2U) \tag{1}$$

$$V_j = V_o \csc(\beta/2)\cos(\alpha + \delta - \beta/2) \tag{2}$$

$$dM_s/dM = \cos^2(\beta/2) \tag{3}$$

$$\tan\beta = \frac{\sin(\alpha + 2\delta) - x \sin\alpha \left[1 - \tan\delta\tan(\alpha + \delta)\right] V_o'/V_o}{\cos(\alpha + 2\delta) + x \sin\alpha \left[\tan(\alpha + \delta) + \tan\delta\right] V_o'/V_o} \tag{4}$$

where α is the half angle of the conical liner; δ, the angle between the direction an element of the liner travels after being struck by the detonation wave and the normal to the surface of the liner; V_o, the velocity at which the liner travels towards the axis; V_j, the velocity of the jet element formed; β, the angle between the collapsing liner wall and the axis; M_s, the mass of the slug; M, the mass of the liner; and x, the initial axial coordinate of the liner element. Primed quantities are obtained by differentiating with respect to x. The velocity with which the detonation front sweeps along the liner surface is designated by U. For a plane detonation front and a conical liner $U = U_D/\cos\alpha$, where U_D is the detonation velocity of the explosive.

Equations (1) to (4) represent four independent relations involving the five unknown quantities, M_s, β, V_j, V_o, and δ. In principle, the experimental determination of any one of the quantities is sufficient to provide a complete description of the process since Equations (1) to (4) can then be solved for the remaining four quantities. Furthermore, an experimental check on the accuracy of the theory can be obtained by measuring any two of the five quantities. The qualitative accuracy of the jet-formation theory was originally demonstrated[3] by experimentally determining β (x) and $V_j(x)$. Experimental values for $\beta(x)$ were readily obtained from slug-recovery experiments using (3), and $V_j(x)$ was determined from emerging-jet-velocity and jet-collection measurements. By subtracting the slug mass from the corresponding liner mass, the cumulative mass of jet material $M_j(x)$ was determined. It was then possible to determine the value of x corresponding to a given amount of penetration, x(P), by firing through targets of various thickness and collecting the unused jet material. The velocity of the impinging jet, $V_j(P)$, was obtained as a function of penetration depth by measuring the velocity of jets emerging from targets whose thicknesses were varied. The jet velocity corresponding to the liner element located at position x was then obtained by eliminating the penetration from the two functions x(P) and $V_j(P)$. The method of analyzing the data that was used in the original verification of the jet-formation theory is

illustrated by the diagram shown in Figure 2. The general agreement between the β calculated directly from slug-recovery data and the β calculated from (4) showed the theory to be qualitatively correct.

It was recognized that the original study of the collapse process could be improved in at least two respects. First, the jet-collection experiment used in determining $V_j(x)$ was not as accurate as desired. Second, the method of analyzing the data required an experimental curve to be differentiated in order to determine $\beta(x)$, and these values for $\beta(x)$ were used to determine V_o. When (4) is finally used to compute new values of β as a check on the validity of the theory, it is necessary to obtain the derivative of V_o. Obviously this involves terms containing the second derivative of the original experimental data. For this reason, there is some question concerning the numerical accuracy of this method for determining the compatibility of the experimental data with (1) to (4).

Eichelberger[4], in a later study of the problem, completely rejected the jet-collection data. He obtained V_o by integrating (4) using experimental values of β determined from new and more precise slug-recovery experiments. The values of V_o and β were used to compute the jet velocity from which it was possible to obtain the spatial position of the jet elements at any given instant of time. These results were then compared with experimental jet-velocity data in order to obtain a check on the accuracy of the theory. The largest source of uncertainty in this analysis arises from the difficulty in choosing the initial conditions for integrating (4).

Uncertainty in the $V_j(x)$ curve due to inaccuracies in the jet-collection experiment can be circumvented by a more precise experiment in which a radioactive tracer is plated on the inside surface of the liner. The first experiments with radioactive tracers[5] were no more precise than the original jet-collection experiments. However, it was apparent that the radioactive-tracer technique could be used to obtain reliable data for large caliber charges, such as the 105mm test charges used at the Ballistic Research Laboratories. During the past several

years, complete data have been obtained for unconfined charges containing 105mm conical copper liners. This report contains an analysis of the data obtained and represents a complete description of the collapse process for these charges.

REDUCTION OF EXPERIMENTAL RESULTS

The penetration produced by a specific zonal element was determined by plating a band of Ag^{110} on the inside surface of the liner[6]. Ag^{110} was chosen because it is readily detected, giving off both strong gamma and high-energy beta radiation. The physical properties of Ag^{110} are similar to those of copper and it possesses a conveniently long half-life (270 days). The 105mm charge produces a large hole in which the transportation of radioactive material from one part to another by succeeding portions of the jet is sufficiently small so that reproducible data can be obtained. The charges were encased in a 0.375 in. thick plastic body and fired from an 8.25 in. standoff into stacked 6.0 in. by 6.0 in. by 1.0 in. mild-steel plates. The results were sufficiently reproducible to determine the location of the penetration produced by the tagged jet element to within 0.50 inch. The experimental data were interpolated to obtain the penetration depths corresponding to values of x between 4.0 cm and 8.0 cm inclusive. Values of P were determined for every 0.5 cm change in x within this range and checked for numerical accuracy by inverse interpolation. The results are presented in Table I.

The emerging jet velocities were determined by firing the charges from an 8.25 in. standoff into targets whose thicknesses were varied systematically[7]. It should be noted that these charges were not encased in the light-weight plastic bodies used in the radioactive work. However, it was believed that the 0.375 in. plastic casing did not seriously alter the jet-formation process, and all the data were regarded as representative of the charge illustrated in Figure 1. The emerging jet velocities were determined using an oscilloscope and a system of grids, which measured the time required for the jet to travel between two known points in space. This technique for measuring the emerging jet velocities was chosen because it is possible to obtain reliable data at velocities below those for which optical methods can be used. The data obtained with the electronic system were checked

against similar data obtained with a streak camera for those velocities where the optical techniques were applicable. The experimental data were interpolated to obtain jet velocities corresponding to penetration depths that were multiples of 1.0 in. or 2.54 cm. The results were smoothed slightly to eliminate fluctuations in the first differences and checked for numerical accuracy by inverse interpolation. The smoothed values of P and V_j, which were used to represent the emerging-jet-velocity data, are presented in Table II.

The slug mass produced by a liner section was determined by firing sectioned 105mm liners into water and recovering that portion of the slug corresponding to the pertinent liner section[7]. Two 105mm liners were cut at a known reference plane perpendicular to the cone axis. Two liners were used in order to compensate for the metal lost in the machining process. The upper section was weighed, and then the two sections were glued together. The charges were fired into a 10-in. gun barrel filled with water. Two recognizable slugs were recovered per shot, and the one corresponding to the upper section of the cone was weighed. This was done for a number of reference planes, yielding slug mass as a function of cone mass and, simultaneously, cone mass as a function of position along the cone axis. It should be noted that the light-weight plastic bodies previously mentioned were not used in the slug-recovery program.

The experimental data were interpolated to obtain numerical values of slug mass versus cone mass for equal intervals of the cone mass. The values were smoothed to eliminate fluctuations in the first differences and checked for numerical accuracy by inverse interpolation. Results are presented in Table III. The cone mass was also obtained for equal intervals of x in the range between 4.0 cm and 8.0 cm, checked by inverse interpolation, and presented in Table IV. Since the entire penetration is produced by jet elements originating between 4.0 cm and 8.0 cm from the apex of the liner, there is no reason to define the function outside this interval unless penetrations into lower strength materials are to be considered.

DETERMINATION OF THE COLLAPSE VELOCITY

The non-steady theory of jet formation discussed in reference (2) assumes a plane detonation wave throughout the collapse process. This was a valid approximation at the time, as the charges were of considerable length. The experimental results analyzed here were obtained from short charges; hence, the plane-wave approximation is no longer valid. The theory has been generalized for the short-charge geometry by assuming a spherical detonation wave emerging from the point of initiation. The primary difference between the equations for a plane wave and those for point initiation is that U is no longer constant, but instead is given by the relation

$$U = U_D / \cos\gamma \qquad (5)$$

where, for each point on the liner, γ is the minimum angle between the normal to the spherical wave front and the cone wall at the intersection of the detonation wave and the cone wall. One now designates the position of the liner element as a function of time by cylindrical coordinates $r(t)$ and $z(t)$ and determines, as in reference (2), $\tan\beta$ by evaluating $(\partial r/\partial z)_t$ when the liner reaches the axis $(r = 0)$. Equation (4) becomes:

$$\tan\beta = \frac{\tan\alpha + T'V_o\cos A + x\tan\alpha(\delta'\tan A - V_o'/V_o) + T'V_o\cos A}{1 + x\tan\alpha\left[\delta' + (V_o'/V_o)\tan A\right] - T'V_o\sin A} \qquad (6)$$

where $\delta' = \left[V_o'/V_o - U'/U\right]\tan\delta$, $A = \alpha + \delta$, and $T(x)$ is the time at which the detonation wave reaches a position x on the liner.

The method of analysis is illustrated by the diagram in Figure 3. The slug-recovery data were differentiated once in order to obtain a first approximation for the collapse angle, $\beta(x)$. The radioactive-tracer and emerging-jet-velocity data were used to define an empirical $V_j(x)$. Estimates of the collapse velocity for the first portions of the jet were computed using (1) and (2). The values of the collapse

velocity scattered substantially due to fluctuations in the derivative of the slug-recovery data; however, a value between 0.20 cm/μsec and 0.21 cm/μsec was indicated for the collapse velocity corresponding to the tip of the jet: i.e., the liner element located at $x = 4.0$ cm. A value was chosen for the collapse velocity of the element located at $x = 4.0$ cm, and collapse velocities were computed for $x > 4.0$ cm by propagating the solution using the first two terms of a Taylor series; i.e.,

$$V_o(x + \Delta x) = V_o(1 + V_o' \Delta x / V_o). \tag{7}$$

To determine V_o'/V_o, (6) was solved for V_o'/V_o and numerical values calculated using the approximate values of β obtained from the slug-recovery data. At this point new values of β were calculated by solving (1) and (2), using the empirical $V_j(x)$ curve. New values of V_o were calculated using the new values of β and the process repeated until no further change occurred in β. This part of the analysis is an iteration process and is designated in Figure 3 by the heavy arrows. The collapse angle calculated from the jet-velocity curve using the iteration process was brought into satisfactory agreement with the slug-recovery data by making minor adjustments in the value of V_o corresponding to the tip of the jet.

A check on the numerical accuracy was made by fitting the resultant values of V_o with a fourth-degree least-squares polynomial and computing dM_s/dM and V_j. This revealed a systematic difference which was attributable to use of only two terms in the Taylor series. The error was six parts in the fourth figure at $x = 4.5$ cm and four parts in the third figure at $x = 8.0$ cm. These differences were sufficiently small to allow correction by a minor adjustment of the coefficients of the first two terms of the V_o polynomial. The final results of the analysis are presented in Table V.

When calculating the jet and slug parameters from the polynomial for V_o, it was noted that V_o had to have four significant figures in order to obtain a reasonable reproduction of V_j in the region 4.0 cm $\leq x \leq$ 5.5 cm because the computed values of V_j were quite sensitive to the derivative of V_o. Increased accuracy in the derivative of V_o was achieved by computing the collapse velocity from the empirical $V_j(x)$ values and using the slug-recovery data only as a check on the final results. Of course, values of V_o presented in Table V are not accurate to four significant figures because they are based on experimental data.

Graphical comparisons of the results of this analysis with the experimental data are shown in Figure 4 and Figure 5. Figure 4 compares V_o calculated from the fourth-degree polynomial and the experimental values determined at Carnegie Institute of Technology*. The experimental values are questionable in the second figure; however, they serve to demonstrate that the polynomial for V_o is qualitatively correct. Shown also in Figure 4 is a comparison between experimental values of V_j and those calculated from the polynomial for V_o. The latter comparison demonstrates the accuracy with which the polynomial represents the original data.

The jet mass, as well as the jet velocity, is important in determining the diameter of the hole produced by the jet. It is therefore necessary that values of M_j computed from the polynomial for V_o be in accord with experimental observations. Figure 5 shows the excellent agreement between experimental values of M_j, which are plotted as open circles, and the M_j versus M computed from the polynomial for V_o. It should be noted that M_j is defined as $M - M_s$ and therefore includes approximately 4 g of liner material dispersed as fine particles ahead of the penetrating jet.

* R. W. Watson and K. R. Becker, Private Communication.

CONCLUSIONS

Although a large amount of shaped-charge research has been completed, the collapse velocity remains a most difficult parameter to determine accurately. Theoretical computations of V_o have not been refined to the point where they can be used without serious reservations. Direct experimental observations have provided a few values of V_o, but the numerical accuracy of these measurements is questionable in the second figure. The systematic analysis of slug-recovery, emerging-jet-velocity, and radioactive-tracer data is the only method for obtaining accurate numerical values of V_o. The data obtained with 105mm unconfined test charges have been carefully analyzed and a polynomial representation of the collapse velocity has been obtained. Because the slug-recovery data were used only indirectly in determining the polynomial for V_o, the excellent agreement illustrated in Figure 5 shows the non-steady theory of jet formation to be adequate for that portion of the jet able to penetrate mild steel.

ACKNOWLEDGEMENTS

The authors wish to thank R. W. Watson and K. R. Becker for use of their unpublished experimental measurements of the collapse velocity and Mr. A. Merendino, who has kindly made additional measurements of emerging jet velocity needed for this analysis. The authors are also indebted to Mr. G. H. Jonas for checking the numerical accuracy of the results by computing the original jet and slug parameters from a polynomial fit to the collapse velocities.

F. E. Allison

F. E. ALLISON

R. Vitali

R. VITALI

REFERENCES

1. Birkhoff, Garrett, Mac Dougall, Duncan P., Pugh, Emerson M., and Taylor, Geoffrey, Sir. Explosives with Lined Cavities. J. Appl. Phys. 19, 563, June 1948.

2. Pugh, Emerson M., Eichelberger, R. J. and Rostoker, Norman. Theory of Jet Formation by Charges with Lined Conical Cavities. J. Appl. Phys. 23, 532, May 1952.

3. Eichelberger, R. J., Pugh, Emerson M. Experimental Verification of the Theory of Jet Formation by Charges with Lined Conical Cavities. J. Appl. Phys, 23, 537, May 1952.

4. Eichelberger, R. J. Re-Examination of the Nonsteady Theory of Jet Formation by Lined Cavity Charges. J. Appl. Phys., 26, 398, April 1955.

5. Bryan, G. M., Eichelberger, R. J., MacDonald, D. and Zigman, P. E. Application of Radioactive Tracers to the Study of Shaped Charge Phenomena. J. Appl. Phys. 28, 1152, October 1957.

6. Gainer, M. K. The Application of Radioactive Tracers to Shaped Charge Liners. BRL Memorandum Report No. 1242, January 1960.

7. Feldman, James B., Jr. Volume-Energy Relation From Shaped Charge Jet Penetrations, Proceedings of the Fourth Symposium on Hypervelocity Impact, APGC-TR-60-39 (II), September 1960.

TABLE I

Tabulated values of the penetration P as a function of the axial position x of the liner element producing the penetration. The tabulated values are based on radioactive-tracer data and the numerical accuracy is checked by inverse interpolation.

x cm	P cm
4.0	0.0
4.5	1.4
5.0	3.1
5.5	4.7
6.0	7.4
6.5	12.3
7.0	20.9
7.5	34.6
8.0	41.2

Original Data		Inverse Interpolation
x cm	P cm	P cm
4.32	0.6	0.6
5.59	5.1	5.1
6.86	17.8	17.8
7.66	38.1	37.2
8.47	42.5	42.4

TABLE II

Tabulated values of the impinging jet velocity V_j as a function of the penetration depth P. The tabulated values are based on emerging-jet-velocity data and the numerical accuracy is checked by inverse interpolation.

Emerging Jet Velocity

P cm	V_j cm/μ-sec
0	0.701
2.54	0.647
5.08	0.601
7.62	0.560
10.16	0.524
12.70	0.491
15.24	0.461
17.78	0.434
20.32	0.409
22.86	0.387
25.40	0.368
27.94	0.349
30.48	0.330
33.02	0.311
35.56	0.293
38.10	0.276
40.64	0.261
43.18	0.245

Original Data		Inverse Interpolation
P cm	V_j cm/μ-sec	V_j cm/μ-sec
0	0.701	0.701
2.54	0.643	0.647
5.08	0.601	0.601
10.16	0.523	0.524
15.24	0.462	0.461
20.32	0.408	0.409
27.94	0.350	0.349
35.56	0.293	0.293
43.18	0.245	0.245

TABLE III

Tabulated values of the cumulative slug mass as a function of cumulative cone mass. The tabulated values are based on slug-recovery data and the numerical accuracy is checked by inverse interpolation.

Cone Mass g	Slug Mass g
0	0.0
10	9.3
20	18.6
30	27.8
40	37.0
50	46.2
60	55.4
70	64.6
80	73.7
90	82.6
100	91.5
110	100.4
120	109.3
130	118.0
140	126.5
150	134.8
160	142.8
170	150.4
180	157.7
190	164.7
200	171.5
210	178.3
220	185.0

Original Data		Inverse Interpolation
Cone Mass g	Slug Mass g	Slug Mass g
20.6	19.1	19.2
41.7	38.7	38.6
69.9	64.6	64.5
103.1	94.3	94.3
122.9	112.0	111.8
142.1	127.9	128.2
166.3	147.7	147.6
188.9	163.9	163.9
213.6	180.5	180.7

TABLE IV

Tabulated values of cumulative cone mass as a function of the axial coordinate measured from the virtual apex of the liner. The tabulated values are based on slug-recovery data and the numerical accuracy is checked by inverse interpolation.

x cm	M g
4.0	51.7
4.5	65.8
5.0	81.7
5.5	98.3
6.0	117.2
6.5	136.7
7.0	159.3
7.5	182.1
8.0	206.1

Original Data		Inverse Interpolation
x cm	M g	M g
4.645	69.93	70.21
5.645	103.13	103.52
6.149	122.90	123.04
6.639	142.10	142.65
7.146	166.33	166.07
7.653	188.87	189.20

TABLE V

Tabulated values of the jet and slug parameters computed from the fourth-degree polynomial representation of the collapse velocity.

x cm	V_o cm/μ-sec	V_j cm/μ-sec	dM_s/dM
4.0	0.2050*	0.712	0.921
4.5	0.2069	0.668	0.907
5.0	0.2065	0.635	0.897
5.5	0.2046	0.603	0.888
6.0	0.2013	0.562	0.874
6.5	0.1958	0.501	0.848
7.0	0.1870	0.417	0.799
7.5	0.1729	0.319	0.709
8.0	0.1509	0.225	0.578

* $V_o = -0.197898 + 0.288477x - 0.0775152x^2 + 0.00942615x^3 - 0.000445364x^4$ for $4.0 \text{ cm} \leq x \leq 8.0 \text{cm}$

DIMENSIONS	
A	3.25"
B	3.40"
C	6.00"
D	0.106"

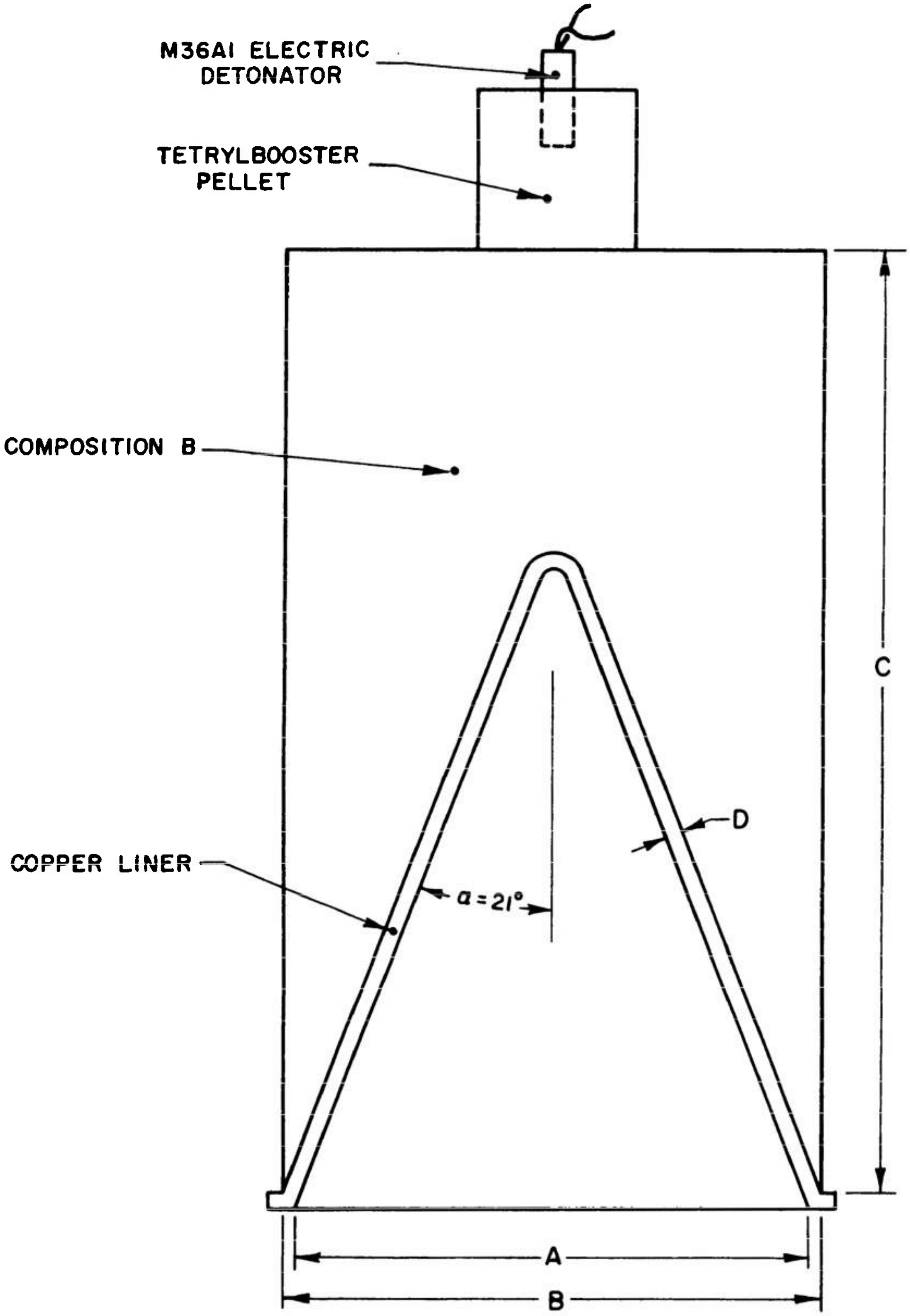

Figure 1: The 105mm unconfined test charge used at the Ballistic Research Laboratories. Pertinent dimensions are shown in the table.

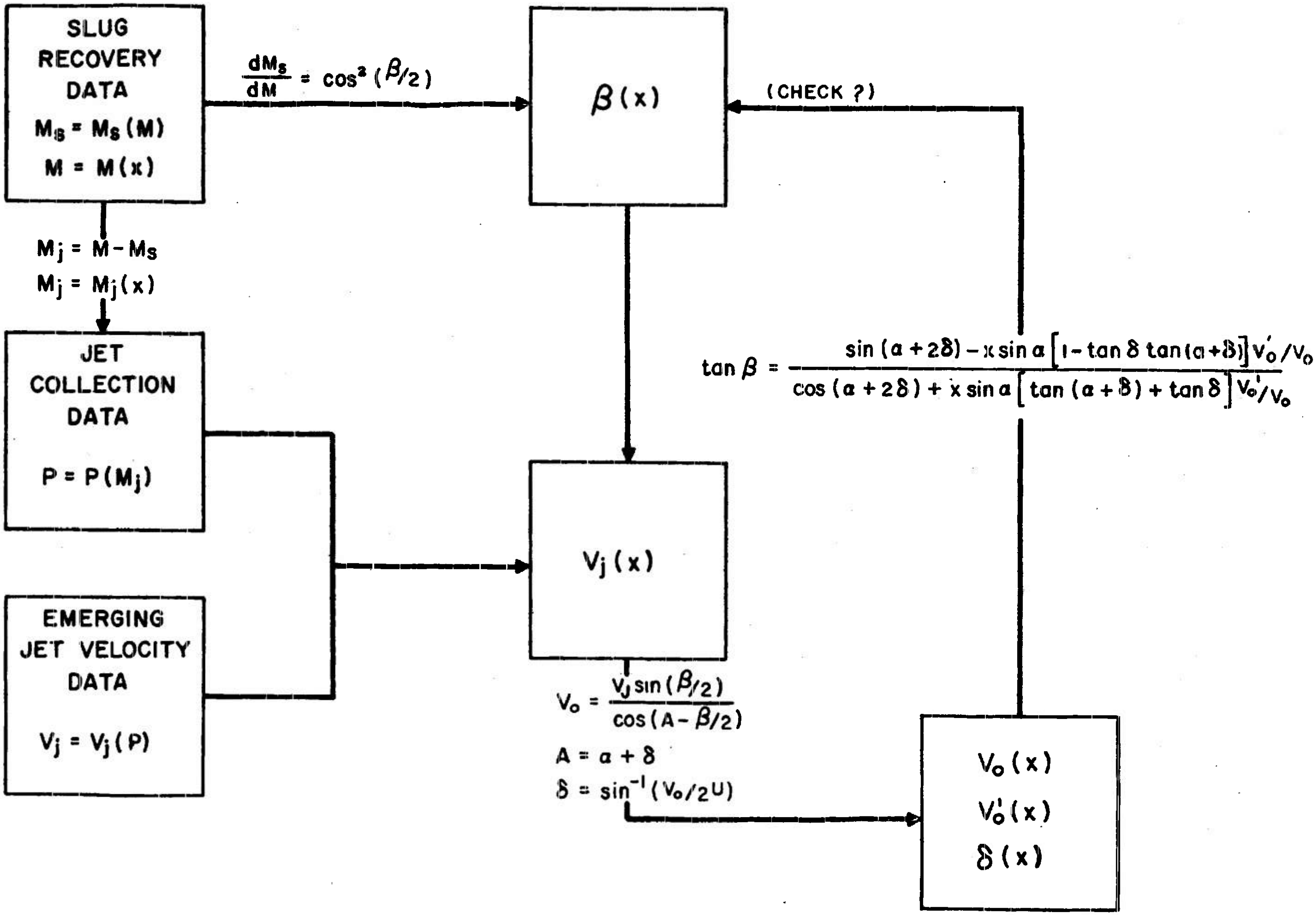

Figure 2: The method used to analyze the slug-recovery and jet-collection data.

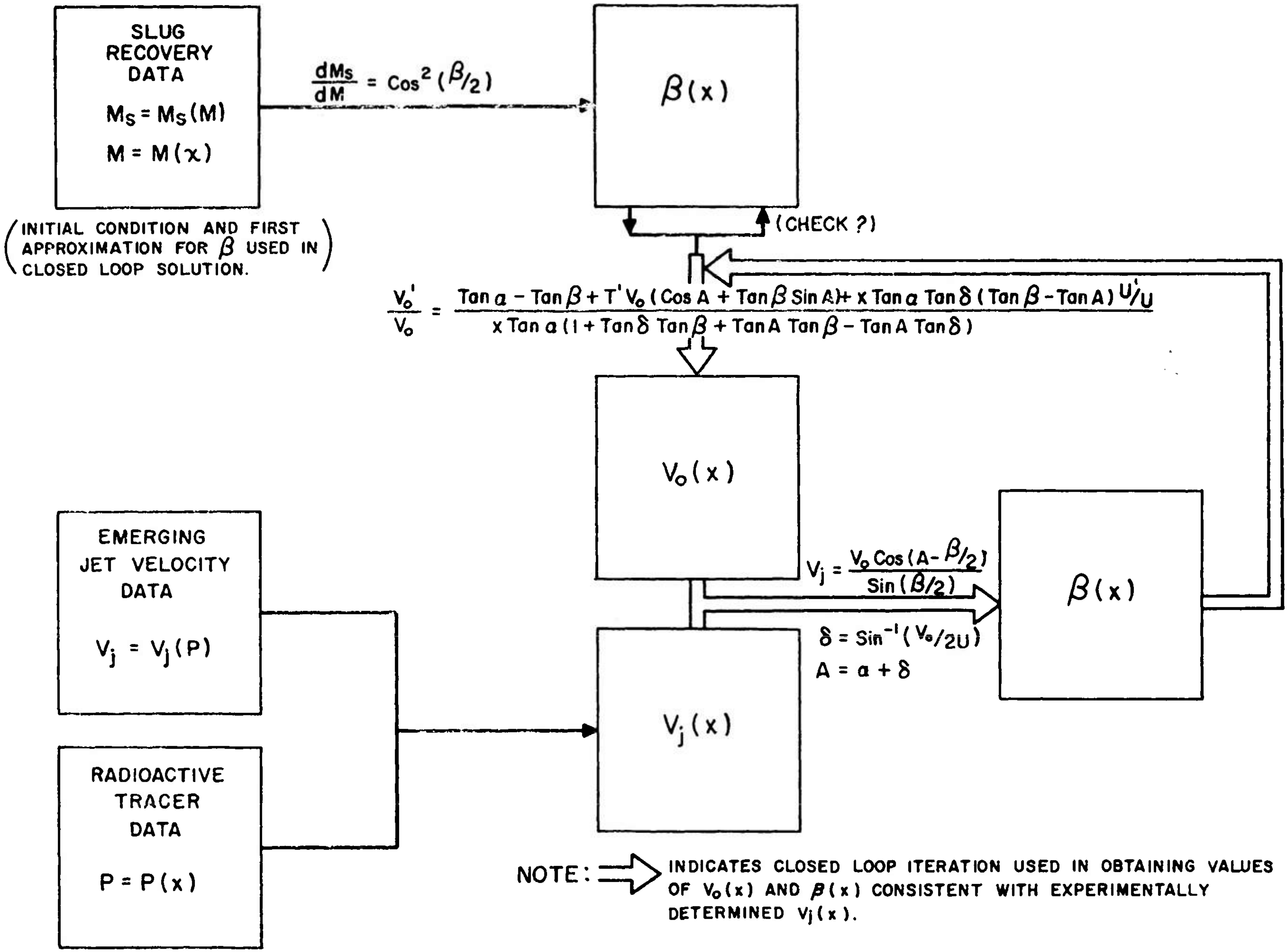

Figure 3: Method used to analyze the data obtained with the 105mm unconfined charge.

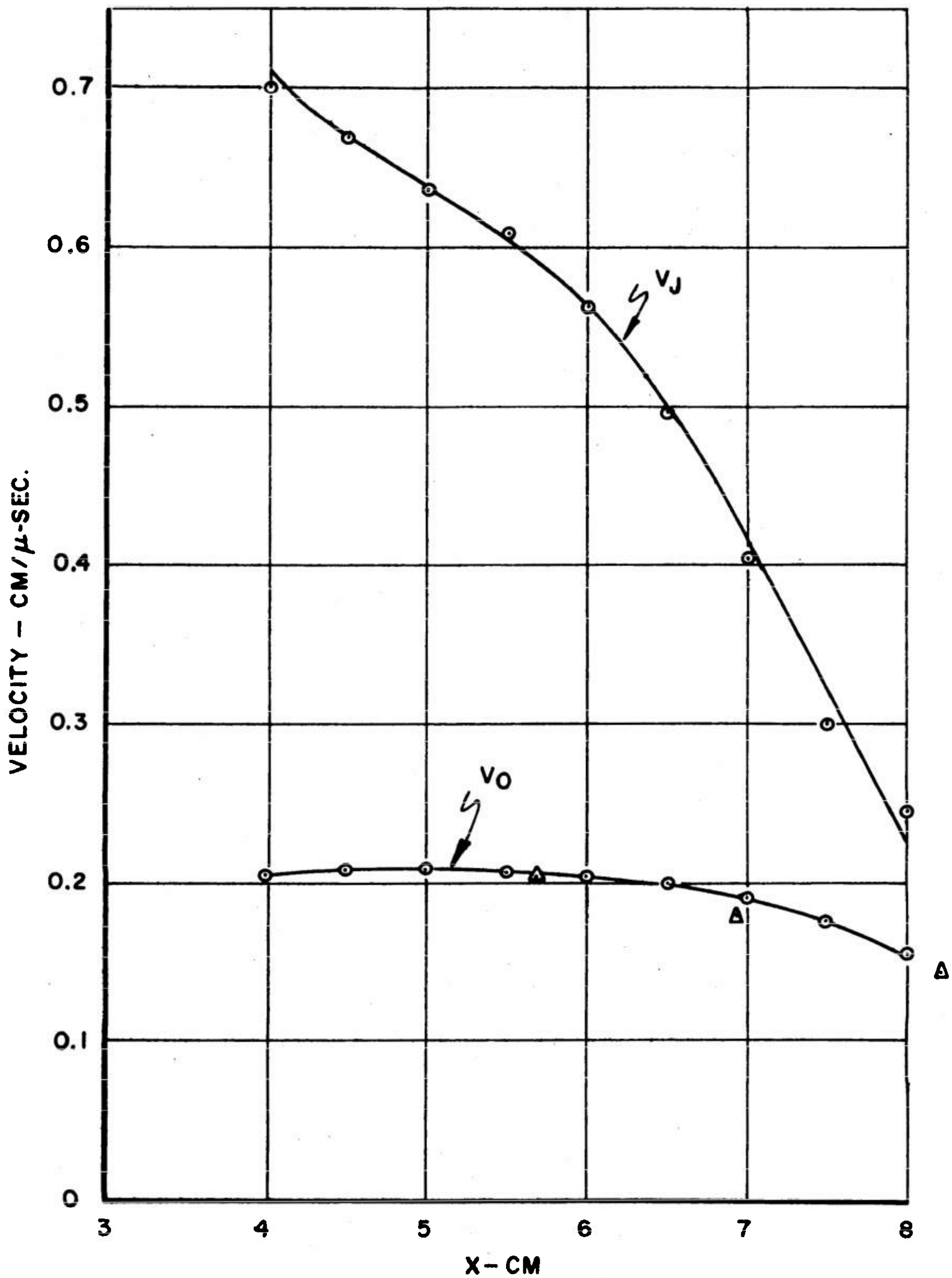

Figure 4: Results obtained from an analysis of the emerging-jet-velocity and radioactive-tracer data for the 105mm unconfined shaped charge. The open circles represent results obtained from a numerical analysis of the data, the triangles represent experimental values obtained at C. I. T., and the curves represent values computed from a polynomial fit to V_o.

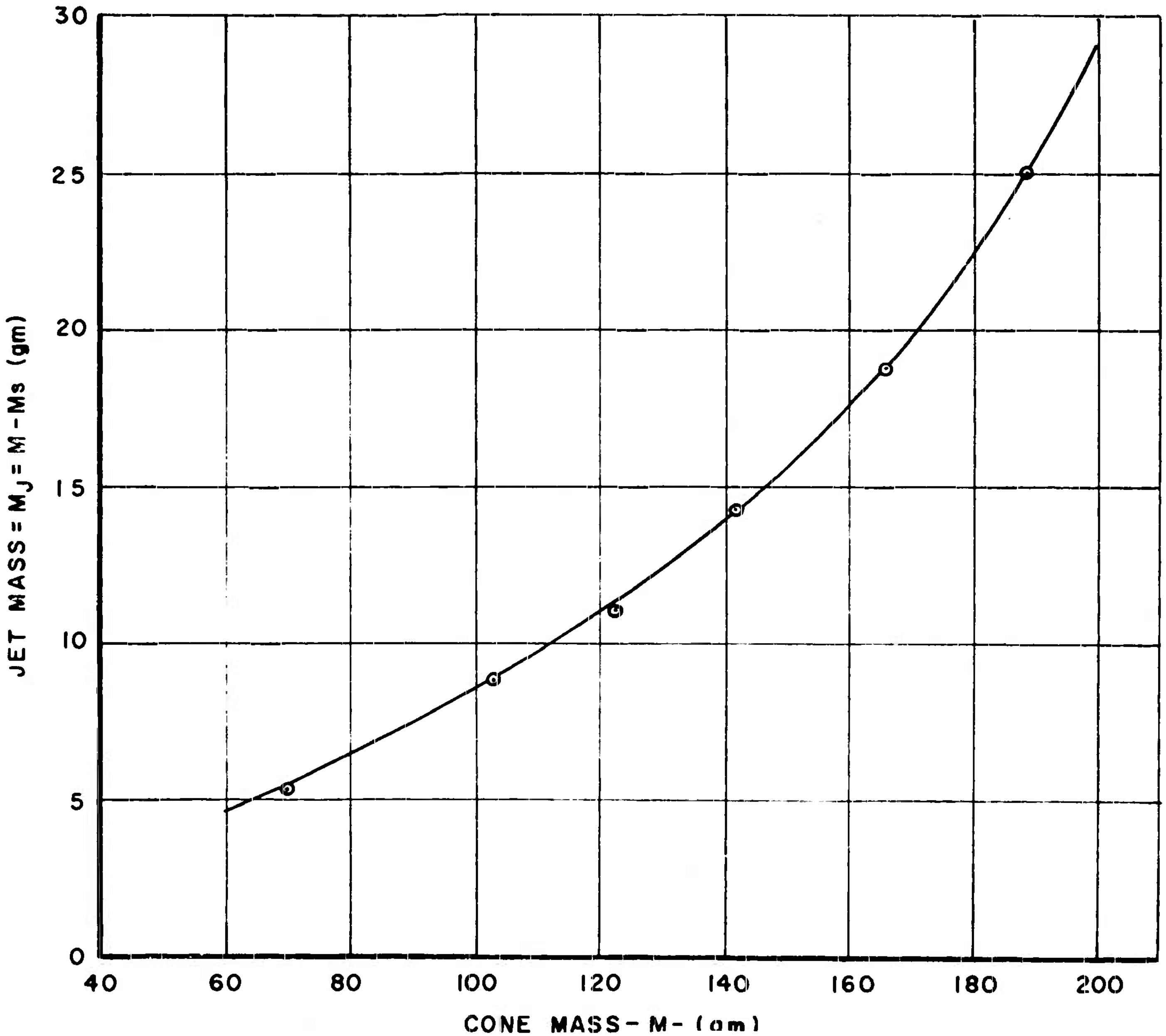

Figure [illegible]: Results obtained from an analysis of the slug-recovery data for the 105mm unconfined charge. The open circles represent results obtained from a numerical analysis of the data, and the curve represents values computed from a polynomial fit to V_o.

DISTRIBUTION LIST

No. of Copies	Organization
10	Commander Armed Services Technical Information Agency ATTN: TIPCR Arlington Hall Station Arlington 12, Virginia
2	Chief of Ordnance ATTN: ORDTB - Bal Sec ORDTW Department of the Army Washington 25, D.C.
1	Commanding General Frankford Arsenal Philadelphia 37, Pennsylvania
1	Commanding Officer Detroit Arsenal Centerline, Michigan
3	Commanding Officer Picatinny Arsenal ATTN: Feltman Research and Engineering Laboratories Dover, New Jersey
1	Commanding Officer Rock Island Arsenal Rock Island, Illinois
1	Commanding Officer Watertown Arsenal ATTN: W.A. Laboratory Watertown 72, Massachusetts
1	Commanding Officer Watervliet Arsenal ATTN: Dr. Robert E. Weigle Chief, Research Branch Watervliet, New York
1	Commanding Officer Diamond Ordnance Fuze Laboratories ATTN: Technical Information Office Branch 012 Washington 25, D.C.
1	Commanding Officer Diamond Ordnance Fuze Laboaratories Washington 25, D.C.
2	Commanding General Ordnance Ammunition Command ATTN: ORDLY-AR-V ORDLY-AR-AR Joliet, Illinois
1	Commanding General Ordnance Weapons Command ATTN: Research Branch Rock Island, Illinois
1	Commanding General U.S. Army Ordnance Missile Command ATTN: Technical Library Redstone Arsenal, Alabama
1	Commanding Officer Springfield Armory ATTN: Res. 4 Div. - T.I.V. Springfield 1, Massachusetts
1	Commanding Officer Army Research Office (Durham) Box CM, Duke Station Durham, North Carolina
3	Chief, Bureau of Naval Weapons ATTN: DIS-33 Department of the Navy Washington 25, D.C.
2	Commander Naval Ordnance Laboratory White Oak, Silver Spring 19, Maryland
1	Commander U.S. Naval Ordnance Test Station ATTN: Technical Library China Lake, California
1	Director U.S. Naval Research Laboratory ATTN: Technical Information Division Washington 25, D.C.

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander U.S. Naval Weapons Laboratory Dahlgren, Virginia
1	Commander Air Force Systems Command ATTN: SCRR Andrews Air Force Base Washington 25, D.C.
4	Commander Air Proving Ground Center ATTN: PGAPI PGTW PGTWR PGTZ Eglin Air Force Base, Florida
1	U.S. Atomic Energy Commission ATTN: Technical Reports Library Mrs. J. O'Leary for Division of Military Application Washington 25, D.C.
1	Library of Congress Technical Information Division ATTN: Bibliography Section Reference Department Washington 25, D.C.
1	U.S. Department of Interior Bureau of Mines ATTN: M.P. Benoy - Reports Librarian Explosives Research Laboratory 4800 Forbes Street Pittsburgh 13, Pennsylvania
1	Firestone Tire & Rubber Company ATTN: Mr. C.M. Cox - Librarian Defense Research Division Akron 17, Ohio
1	Applied Physics Laboratory The Johns Hopkins University 8621 Georgia Avenue Silver Spring, Maryland
1	Carnegie Institute of Technology ATTN: Professor Emerson M. Pugh Department of Physics Pittsburgh 13, Pennsylvania
10	The Scientific Information Officer Defence Research Staff British Embassy 3100 Massachusetts Avenue, N.W. Washington 8, D.C.
4	Defence Research Member Canadian Joint Staff 2450 Massachusetts Avenue, N.W. Washington 8, D.C.